Metasurface Inspired Resonators for Application in One-to-many Wireless Power Transfer System

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Abstract—This work is devoted to the study of one-to-many wireless power transfer systems with magnetic resonant coupling. We develop metasurface-inspired resonators with quasi-uniform near magnetic field distribution to use as a transmitter for simultaneous wireless charging of multiple receivers placed on it. Two different topologies of compact multi-mode resonators formed as an array of parallel wires with a capacitive load are proposed and studied. We perform circuit analysis and full-wave numerical simulations to study the electromagnetic characteristics of the resonators. The benefits of their application in one-to-many wireless power transfer systems are also discussed. For an experimental demonstration of the performance of the proposed resonators, we fabricate two one-to-many wireless power transfer systems based on them. The first one operates at 17 MHz, the second one operates at 200 kHz. Both systems are able to simultaneously charge several receivers placed on it. The wireless power transfer system operating at 200 kHz was implemented as a chessboard. For the 5 W input power, the system can charge up to 32 receivers which are made as a chess pieces with inserted light-emitting diodes and illuminate during the play standing at the chessboard.

Index Terms—Metasurface, near magnetic field, resonator, wireless power transfer.

I. INTRODUCTION

The concept of wireless power transfer (WPT) was appeared first time at the beginning of the XX century and belonged to N. Tesla [1], but it was not widely used due to insufficient development of technology at that point. Everything was changed over the past two decades: the intensive development of consumer electronics, the appearance of the Internet of Things concept, and its real-world applications have led to the rapid growth of the portable electronic devices used by people. Each of these devices requires regular charging and the use of conventional power cords becomes inconvenient for users. This became an impetus for the active development of WPT technology [2].

For the present, WPT is applied to increase the convenience of electronic device usage. Methods of energy transfer to a single receiver are widely developed, and currently, the design of WPT systems that are capable to simultaneously charge several devices for further improvement of user experience is a much more important task. Near-field one-to-many WPT is one of the promising solutions to this. It uses only a single transmitter which does not require any complex power control scheme, in opposite to many-to-many WPT, which requires receiver position detection and a complicated power scheme to switch between unit transmitter coils to control the charging.

The main challenge in one-to-many WPT system design is maintaining of the high transmission efficiency, which is not dependent on misalignment or amount of receivers. To provide this property a uniform magnetic field distribution should be created over the transmitter area. This will ensure a constant coupling coefficient between the transmitter and the receivers for their any position.

The conventional planar spiral coils can be optimized in order to obtain uniform field distribution. For example, in [3] and [4] genetic algorithm was applied to minimize the variation of the magnetic field in the working area of the transmitter. There is also another approach for creating a uniform field distribution, namely, the use of metasurface-inspired resonators [5], [6], which have specific advantages over the planar spiral coils. For example, they can provide more flexible magnetic field control, reduce the electromagnetic exposure of users, and provide multi-frequency operation.

In this work, we propose two different topologies of compact metasurface-inspired resonators with quasi-uniform magnetic field distribution. One of which is based on a truncated left-handed transmission line and is more suitable for high-frequency applications, while the other one is based on a truncated right-handed transmission line and is suitable for low-frequency application. We perform the equivalent circuit and full-wave analysis for both topologies. The prototypes of the one-to-many WPT systems based on metasurface-inspired resonators operating at 17 MHz and 200 kHz were fabricated for demonstration of the WPT performance.

II. DESIGN AND ANALYSIS

A. Metasurface-Inspired Resonators for WPT

Multi-mode metasurface-inspired resonator for WPT was introduced in [7]. The equivalent circuit and the fabricated prototype are shown in Fig. 1(a) and Fig. 1(b) respectively. The resonator is formed as an array of 15 parallel wires connected through capacitors. The original resonant frequency of wires is equal to the half-wavelength electric dipole resonance. Due to the subwavelength arrangement of wires, the strong coupling occurs between them, which leads to the splitting of...
dipole mode resonance into 15 different modes with a unique magnetic field distribution each. It was observed that the fundamental mode has a quasi-uniform magnetic field profile above the resonator and can be utilized for one-to-many WPT applications.

Near-field WPT systems usually operate in the range of hundreds of kHz (Qi standard) to several MHz (ISM radio band). However, for the array of bare wires the fundamental mode frequency remains higher than this range. To adapt the metasurface-inspired resonator for the standard frequencies the electric length of each wire should be tuned. In [7] it was done by adding the capacitors in parallel to the wires, as shown in Fig. 1(a). It can be noticed that a unit cell of this structure is a high-pass filter section. This topology can be considered as a truncated left-handed transmission line [8] which occurs to be a sub-wavelength resonator with a number of modes determined by the dispersion of the line. For the left-handed transmission line, the inverted order of modes is observed, which means that the fundamental one, with uniform magnetic field distribution, is observed on the highest frequency of all modes.

The electrical length of the wires can be also increased by adding the capacitors in series to each wire, as shown in the equivalent circuit in Fig. 1(c). In this case, the unit cell of the structure represents a low-pass filter section, and that topology can be considered as a truncated right-handed transmission line. It also occurs to be a sub-wavelength resonator, but with a normal order of modes, when the uniform magnetic field distribution is observed on the lowest frequency of the band. Since the unit cell of this resonator is a low-pass filter section, further we will refer to it as a low-pass resonator. For the structure with a high-pass filter unit cell, we will refer to it as a high-pass resonator.

**B. Equivalent Circuit Analysis**

The characteristics of metasurface-inspired resonators can be obtained by means of the equivalent circuit analysis (Fig. 1(a) and Fig. 1(c)). Each wire can be represented by its self-inductance $L_c$. For the round wires the self-inductance (in nH) can be calculated as:

$$L_c = \frac{2L'}{\ln\left(\frac{2L'}{r}\right) - \frac{3}{4}},$$

where $L'$ and $d$ is a physical length and radius of the wire measured in cm [9]. For the wires with rectangular cross section realised by printed circuit board technology the self-inductance (in nH) can be estimated as:

$$L_c = 2L'\left(\ln\left(\frac{2L'}{w+\tau}\right) + \frac{1}{2}\right),$$

where $L'$, $w$ and $\tau$ is a physical length, width and thickness of the printed wire measured in cm [9].

The inductance $L_s$ represents the self-inductance of the contact pads where the capacitors are mounted. Their value can be also estimated by the formulas above. The conductive losses were neglected in the presented equivalent circuits. The
load capacitance $C$ is connected in series to the wires for the low-pass resonator and in parallel to the wires for the high-pass resonator. For a given length, a number of wires, and spacing between them (which defines the $L_s$ value) the resonant frequency can be optimized just with $C$ tuning.

In this work, we develop a high-pass resonator (Fig. 1(a-b)) formed by 15 printed conductors with 0.5 cm width and the 40 cm length placed with 2 cm spacing. The equivalent circuit model was build for this structure: the self-inductance values $L_c$ and $L_s$ were calculated using equation 2, the capacitance $C$ was optimized to tune the fundamental mode frequency to 17 MHz. The resulted values are listed in Table I. At Fig. 2(a) the input impedance of the optimized structure is shown. Inverted order of modes can be seen: the first mode has the highest frequency of this group of modes. That makes it easier to tune the resonator on high frequencies because it will require lower capacitance $C$. The number of resonances corresponds to the number of wires (or unit cells) of the resonator.

The low-pass resonator (Fig. 1(c-d)) was formed by 16 round wires with 0.4 cm radius and 41 cm length placed with 3.4 cm spacing. The self-inductance values were calculated using equation 1, the equivalent circuit was optimized to the 200 kHz by the capacitance $C$ inserted in series to the wire. The values of all equivalent parameters are listed in Table I. The input impedance of the low-pass structure is shown in Fig. 2(b). It can be seen that the resonator has a normal dispersion of modes and the first mode has the lowest frequency of this group of modes. That makes it easier to tune the resonator on low frequencies.

### C. Magnetic field

The full-wave electromagnetic analysis of the high-pass and low-pass resonators was performed in CST Microwave Studio 2020 in order to check the circuit analysis results and calculate the field distribution. The normal component of the magnetic field on the fundamental mode at the 15 mm height is shown in Fig. 4(a) for the high-pass resonator and in Fig. 4(b) for the low-pass resonator. It can be seen that the field profiles are similar for both resonators. The field is quasi-uniform and has a large area with a high magnetic field in the center. That makes it possible to apply these resonators in one-to-many WPT systems as a transmitter. They will provide a high coupling coefficient between them and receivers, and it will not dramatically change with their different positions.

### III. One-to-Many WPT System Demonstration

In this work, we realize two one-to-many WPT systems with multi-mode metasurface-inspired resonator transmitters. The
operation of the system with a high-pass resonator is demonstrated in Fig. 3(a-c). The resonator itself has 40 cm × 30 cm size and can accommodate several receivers on it. Printed multi-turn spiral coil receivers were fabricated on a 2 mm thick FR-4 PCB board. It was tuned to the operating frequency by a 470 pF series capacitor. Also, a full-bridge rectifier made of Schottky diodes was fabricated to supply the DC power to the light-emitting diode (LED) loads. Three receivers were placed in different positions on the resonator to show the misalignment stable efficiency of the WPT system.

The operation of the system based on a low-pass resonator is demonstrated in Fig. 3(d-f). The transmitter with 40 cm × 50 cm size was installed into the chessboard. The chess pieces were made of transparent polymer resin with embedded perovskite quantum dots. The quantum dots begin to fluoresce when irradiated with light of a certain wavelength. For that purpose LED diodes incorporated inside of the chess pieces have been used. To deliver a current to the LEDs receiving multi turn coils were placed inside the base of the chess piece. They were tuned to the operating frequency by a 15 nF capacitor. A voltage doubler was used as a rectifier. As soon as the chess piece stands on the chessboard the power is transferred wirelessly and a LED illuminates a chess piece. The input power of the system is 5 W. The transmitter can accommodate 32 chess pieces simultaneously and power up all the LEDs as one can see from Fig. 3(d-f).

IV. CONCLUSION

The multi-mode metasurface-inspired resonators with high-pass and low-pass topologies were proposed. The equivalent circuit models of the resonator were derived and studied. The different mode dispersion is observed in these structures, which makes a high-pass resonator more suitable for high-frequency (ISM radio band) applications, and a low-pass resonator more suitable for low-frequency applications. At the fundamental mode for both structures, the magnetic field has a quasi-uniform distribution, which is required for one-to-many WPT. Two one-to-many WPT systems were fabricated with these resonators to experimentally demonstrate the WPT performance. The first system works at 17 MHz, the second one – at 200 kHz. The misalignment robust WPT was shown for several receivers charging simultaneously.

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